11CV-0135

Long Term Hydrogen Vehicle Fleet Operational Assessment

Steven Eick, Greg Whiting, Rene Parker
TARDEC, Select Engineering Services, Select Engineering Services

ABSTRACT

The U. S. Army Tank Automotive Research, Development and Engineering Center (TARDEC) National Automotive Center (NAC) owns a fleet of ten Hydrogen Hybrid Internal Combustion Engine (H2ICE) vehicles that have been demonstrated in various climates over the past two years. This included demonstrations in Michigan, Georgia, and California. Between July of 2009 and January of 2011, the fleet of ten H2ICE vehicles was deployed to Oahu, Hawaii for long-term duration testing.

The operation of the H2ICE vehicles in Hawaii utilized standard operation of a non-tactical vehicle at a real-world military installation. The vehicles were fitted with data acquisition equipment to record the operation and performance of the H2ICE vehicles; maintenance and repair data was also recorded for the fleet of vehicles. Over the year-long demonstration, the vehicles were driven by a wide range of military services including the Army, Air Force, Navy, Pacific Command (PACOM) and National Guard; each service had different drive cycles. Drivers were trained in the operation of the H2ICE vehicles and the safe use of hydrogen, and were surveyed to solicit their feedback on the H2ICE vehicles.

The demonstration of this fleet of H2ICEs identified maintenance issues associated with long term operation of the vehicles, as well as user concerns that would need to be addressed if hydrogen vehicles are going to be transitioned from research and development fleets to general commercial use vehicles. Vehicle performance data collected showed the fuel efficiency of the fleet of vehicles and the vehicle's reliability.

INTRODUCTION

The NAC is an organization within U.S. Army TARDEC that serves as a facilitator between the Government, Academia, and Industry to develop and evaluate mobility and energy related technologies within real-world settings. The implementation and qualification of these technologies addresses national objectives and improves the state of the art to advance military operational support capabilities.

One area of interest to the NAC is the deployment of hydrogen vehicles in non-tactical, administrative fleets at military installations in the United States. In this paper, non-tactical vehicles refer to commercial vehicles utilized by Military personnel and Department of Defense civilians on Government Installations in an administrative function and not for any tactical missions. Deployment of hydrogen vehicles helps meet emission requirements, reduction of petroleum consumption and increased use of alternative fuels. TARDEC purchased ten hydrogen hybrid internal combustion engine (H2ICE) vehicles; these vehicles were intended to be utilized in non-tactical Department of Defense (DOD) applications. The H2ICE vehicles are a standard gasoline hybrid vehicles converted to burn pure hydrogen in the gasoline engine. The H2ICE vehicles after their conversion only combust hydrogen gas; they are not a bi-fuel vehicle and can no longer operate on gasoline. At the start of this data collection period, the H2ICE vehicles had been operated for two years.

This paper details the information gathered regarding the use, maintenance and support required by the fleet of ten H2ICE vehicles being operated in Hawaii from July 2009 to January 2011. This includes lessons learned from the operation of the fleet of vehicles, driver adoption of the fleet, and noted maintenance actions required to keep the H2ICE fleet operational.

METHODOLOGY

A fleet of ten H2ICE vehicles was deployed to the island of Oahu, Hawaii to operate in real-world conditions. This location was chosen due to the availability of hydrogen at Joint Base Pearl Harbor-Hickam (JBPHH) and the clustering of DOD services including the Army, Air Force, Navy, Marines, PACOM, Coast Guard and National Guard. Drivers were selected from the various military organizations based on their commitment to utilize the vehicle a minimum of 200 miles (322 km) per month and their proximity to JBPHH for refueling. All drivers were Government personnel or Government contractor personnel that had self identified or were

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **21 MAR 2011**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**

4. TITLE AND SUBTITLE **Long Term Hydrogen Vehicle Fleet Operational Assessment**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) **Steven Eick; Greg Whiting; Rene Parker**	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **US Army RDECOM-TARDEC 6501 E 11 Mile Rd Warren, MI 48397-5000, USA**	8. PERFORMING ORGANIZATION REPORT NUMBER **21622RC**
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) **US Army RDECOM-TARDEC 6501 E 11 Mile Rd Warren, MI 48397-5000, USA**	10. SPONSOR/MONITOR'S ACRONYM(S) **TACOM/TARDEC/RDECOM**
	11. SPONSOR/MONITOR'S REPORT NUMBER(S) **21622RC**

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**SAR**	**7**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

recommended for having a requirement to drive regularly during their workday. The driving cycles generally involved one of two types of trips: low speed, on base driving with multiple stops and long distance, high speed driving such as driving to and from another installation on Hawaii's Interstates. About 68% of the driving events recorded were lower speed, city driving cycles.

All the vehicles were fitted with data acquisition equipment that is capable of collecting operational data while the vehicle is running. All data is transmitted to a password protected website. Additionally, all maintenance and repair actions were tracked throughout the duration of the project to monitor and determine long term maintenance needs from the use of H2ICE vehicles in extended operation. Driver experiences were collected through interviews and surveys.

HARDWARE

VEHICLES

The ten H2ICE vehicles were the standard model year 2008 Hybrid Gasoline Electric Sport Utility Vehicles (SUV). Figure 1 shows one of the H2ICE vehicles. The H2ICE vehicles have a full hybrid system capable of propelling the vehicle using, electric power, engine power, or both together. The system has an engine shut-off for when the vehicle is stopped and can go full electric up to roughly 25 miles per hour (40kilometers per hour) before the internal combustion engine is started. The standard vehicles underwent a conversion process where the 15-gallon gasoline fuel systems were replaced with type-IV carbon-fiber hydrogen tanks and appropriate fuel lines. The type-IV tanks have a service pressure of 350 bar and were connected in series with check valves that locked the tanks when the vehicle loses power. The replacement hydrogen storage system can hold 3.8 kg of gaseous hydrogen at a pressure of 350 bar.

Figure 1 – A H2ICE Vehicle in Hawaii

The engines used in the H2ICE vehicles was the standard gasoline engine from the manufacturer with a few replaced parts. The standard engine is a 2.3 liter in-line four cylinder engine capable of providing 133 hp (99.1 kW). The engine had the fuel injectors and spark plugs replaced; a new air filter was required. In order to maintain vehicle power during the conversion, a turbocharger was added to make up for the lost engine power seen during the conversion to a gaseous fuel. All of these elements of the conversion were performed by during the conversion process and are protected intellectual property of the Company that performed the conversions. A supercharger on the hydrogen internal combustion engine would also have increased engine output significantly [1]. The high pressure injection of hydrogen into the engine has been investigated to find the best air-fuel ratios and nozzle geometries [2].

The conversion process included installation of hydrogen sensors in the engine compartment and above the storage tanks. The converted H2ICE had a published range of 100 miles or 160.9 km; the range depended on driver and local conditions, and varied above and below the listed range. Due to the nature of hydrogen combustion, carbon dioxide, carbon monoxide and nitric oxide emissions are all very low.

DATA ACQUISITION

The ten H2ICEs vehicles had a data acquisition system collecting data during the operation of the vehicle. The vehicle's CAN bus supplied data on the engine, hybrid battery, and vehicle operation to the data logger; a temperature and pressure sensor on the hydrogen storage system were installed and provided the data logger the state of hydrogen storage tanks and the amount of hydrogen gas remaining in the vehicle. The temperature and pressure sensor were located on the third tank in the series of four tanks. The data acquisition logger was located on the passenger side of the trunk, in the cavity normally housing the tire jack. The data logger used the wireless modem to upload the data to a secure server that organized the information and presented it to a password protected website.

REFUELING

The fleet of H2ICE vehicles refueled at a hydrogen refueling station located at Joint Base Pearl Harbor Hickam in Hawaii. During the demonstration period, this hydrogen refueling station was the only refueling site available on Oahu. This refueling station used solar energy from an array of solar panels to power an alkaline electrolysis unit that generated hydrogen for vehicle refueling. The average refueling event required 10-15 minutes to completely refuel the vehicle, longer than the average time required to refuel a gasoline vehicle. Drivers were trained on basic hydrogen safety requirements, but a dedicated station operator refueled the vehicles.

OPERATIONAL ISSUES

During the operation of the fleet of ten H2ICE vehicles, specific issues came up that reduced overall reliability or usability of the H2ICE vehicles. These issues included electrical problems with the hydrogen fuel system, fuel efficiency on steep grades, and driver concerns with the electrically controlled continuously variable transaxle and turbo-lag. These issues could be largely overcome by further development of the technology.

ELECTRICAL PROBLEMS WITH HYDROGEN FUEL SYSTEM

An issue that was encountered on the fleet of H2ICEs was that the vehicle would start, but not continue to run. This was traced back to the hydrogen sensors having a faulty diode. The installation of a faulty diode was determined to be a single occurrence issue; the failure of the sensor was seen as an issue that could show up as the sensors age. The need for a hydrogen leak sensor is inherent to the vehicle type; this would be an issue that would require additional maintenance attention in a large-scale deployment. However, the electronics involved are expected to be reliable and the additional maintenance would probably not be significant.

Another element of the hydrogen fuel system that encountered an issue was the electronic module that communicates with the dashboard fuel gauge. This caused the fuel gauge to suddenly drop by a quarter of a tank. This caused the fuel gauge to rapidly drop, showing a loss of a quarter of a tank of fuel. This could trigger the low-fuel shut-down that protects the fuel tanks from being depleted by shutting the vehicle down. Once the faulty equipment was replaced, the problem was resolved. In a second generation of this vehicle type, a fuel gauge design that does not attempt to integrate the fuel gauge with the factory fuel gauge electronics would probably prevent this issue from recurring.

VEHICLE PERFORMANCE ON STEEP GRADES

During an interview with a driver, the driver commented that the ascension of the hill to get to Camp Smith, a grade of more than 6% in some spots, caused a significant draw on the hydrogen fuel. By using the data acquisition system to investigate specific occurrences of an H2ICE vehicle driving up the hill to Camp Smith, it could be seen that the consumption of hydrogen by the vehicle to climb the steep grade was significantly greater than was required for similar speeds on flat ground. The time it took to climb the hill was about 6% of the total time, but the hydrogen used during this period was about 30% of the total hydrogen consumed for the trip. Due to the increased hydrogen consumption, the H2ICE vehicles were limited in range when steep grades were involved, causing drivers to avoid utilizing the vehicles. This is similar to problems experienced with battery-powered electric vehicles.

DRIVER CONCERN WITH CONTINUOUSLY VARIABLE TRANSAXLE AND TURBOLAG

The H2ICE vehicles use an electrically controlled continuously variable transaxle (eCVT), which maintained engine speeds higher than drivers were expecting, especially at highway speeds, partly as a result of using hydrogen rather than gasoline as a fuel. The fact

that the eCVT does not shift, accompanied by the high engine RPMs associated with hydrogen fuel in this design caused a large number of reports of the H2ICE vehicles having issues with shifting properly. Because a turbocharger was installed to compensate for the swap from liquid to gaseous fuel, the H2ICE vehicles experienced turbo lag as the feedback in the mechanical system caught up to the operation of the turbocharger. These issues were, together and individually, commonly reported by the drivers as "problems with shifting." These issues did not impact how often the drivers utilized the vehicles, but did affect their comfort in using them and had to be addressed through training the drivers to expect that performance from the H2ICE vehicles.

FUEL ECONOMY

The H2ICE vehicles were investigated for fuel economy during the period of performance of this demonstration. The data collected on the vehicle included the number of miles travelled during the demonstration and the number of kilograms of hydrogen used during the demonstration. Based on a study by Sandia National Labs in 2001, a vehicle designed to optimize efficiency could show an overall efficiency of 40% and be able to get 60 miles per equivalent gallon of gasoline[3]. Table 1 shows the number of miles and kilometers travelled for each vehicle and the total hydrogen usage of the H2ICE vehicle during the demonstration period.

Table 1 – Accumulated Vehicle Distance Traveled and Hydrogen Usage during the H2ICE Demonstration.

Vehicle Number	Miles Traveled Miles (Kilometers)	Hydrogen Usage Kilograms
1	1272 mi (2047 km)	47.3 kg
2	1331 mi (2142 km)	53.3 kg
3	905 mi (1456 km)	39.0 kg
4	2624 mi (4223 km)	116.5 kg
5	1420 mi (2285 km)	55.2 kg
6	3651 mi (5878 km)	109.0 kg
7	7765 mi (12497 km)	244.8 kg
8	5238 mi (8430 km)	205.9 kg
9	1955 mi (3146 km)	89.8 kg
10	4165 mi (6703 km)	152.9 kg

Using the data collected from the vehicles, the average fuel economy was calculated using equation (1). The average fuel economies of each vehicle are presented in Table 2. Also included in Table 2 is the average fuel economy in miles per gallon of gasoline equivalent (gge) and kilometers per gge, calculated by applying the conversion factor of one gge being equivalent to 0.997 kilograms of hydrogen [4].

$$\text{Fuel Economy}\left[\frac{\text{mi}}{\text{kg}}\right] = \frac{\text{Miles Travelled[mi]}}{\text{Hydrogen Usage[kg]}} \qquad (1)$$

Table 2 – Average Fuel Economy of the H2ICE Vehicles for the Period of Performance of the Demonstration.

Vehicle Number	Average Fuel Economy mi/kg (km/kg)	Average Fuel Economy mi/gge (km/gge)
1	26.9 (43.3)	26.8 (43.1)
2	25.0 (40.2)	24.9 (40.1)
3	23.2 (37.3)	23.1 (37.2)
4	22.5 (36.2)	22.4 (36.0)
5	25.7 (41.4)	25.6 (41.2)
6	33.5 (53.9)	33.4 (53.8)
7	31.7 (51.0)	31.6 (50.9)
8	25.4 (40.9)	25.3 (40.7)
9	21.8 (35.1)	21.7 (34.9)
10	27.2 (43.8)	27.1 (43.6)

The results of the total mileage accumulated over the period of vehicle operation and the average fuel economies for each vehicle is represented in the bar chart in Figure 2.

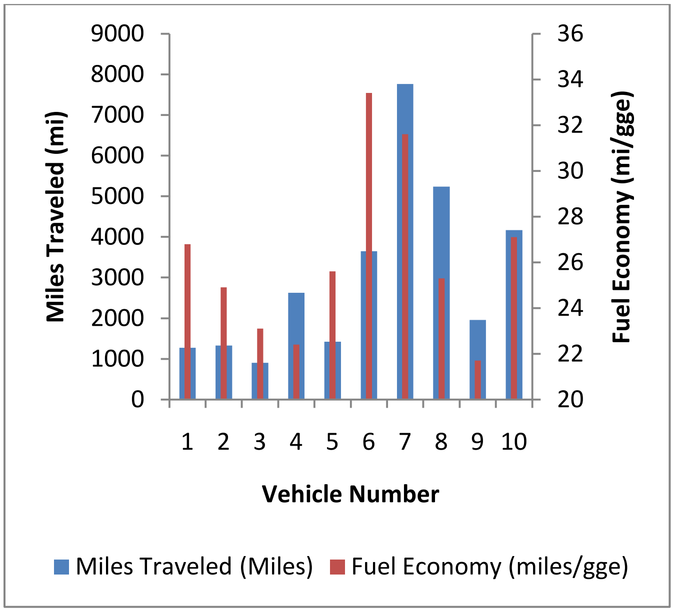

Figure 2 – Individual Vehicle Mileage and Fuel Economy

The average fuel economies of the vehicles varied greatly between vehicles due to the differences in drive cycles of the various organizations and the variation in driving styles between the different drivers. When the ten vehicles' average fuel economies are averaged for the fleet, the fleet fuel economy of 26.2 miles per kilogram hydrogen or 42.2 kilometers per kilogram hydrogen is found. This is comparable to fuel economies of standard hybrid electric-gasoline SUVs [5].

MAINTENANCE ACTIONS

The main areas of discussion for the maintenance actions performed on the H2ICE vehicles during the demonstration period are the effects of the greater water levels in the exhaust, and the 12V starting, lighting and Ignition (SLI) battery. These were areas that required additional attention to maintain the H2ICE vehicles in an operational status. The standard maintenance items not discussed in this section were not different in the number of occurrences seen in standard gasoline vehicles.

EFFECTS OF WATER ON EXHAUST AND ENGINE LUBRICATION

During the demonstration period, the H2ICE vehicles had an occurrence of the muffler rusting internally due to the water in the exhaust. This caused an early replacement of the muffler of several of the vehicles with a stainless steel muffler. During the demonstration, the oil was regularly checked for visual signs of water contamination. The vehicle utilized a 5W-15 synthetic oil in the engine for lubrication. The high levels of water in the exhaust combined with cool intake air allow condensing water to enter the crankcase. When an oil sample was tested, it was indicated that there was a moderate level of water present, and the gycol test was negative. Though much more noticeable in cooler climates, the small amount of water in the oil can have a significant effect. Water contamination in lubricating oil can cause premature oil breakdown and corrosion and pitting of internal engine components [6]. In these vehicles, oil testing has revealed that oil changes at a 3000 mile (4828 kilometer) interval are sufficient to control the water in a moderate climate. This is significantly more often than the planned schedule of an oil change every 5000 miles (8047 kilometer). In a second generation, use of a desiccant filter could be tested as a potential long-term solution to this problem.

As stated above, the standard gasoline engine was modified to burn hydrogen on the H2ICE vehicles. A dedicated hydrogen internal combustion engine generally has unique valves and pistons in addition to the fuel injection, ignition and air induction systems [7][8].

STARTING, LIGHTING AND IGNITION BATTERY

During the demonstration period, the 12V SLI battery caused electrical system reliability issues within the H2ICE vehicles. The combination of the factory electronics, the hydrogen systems, and the added draw from the data acquisition units generated a parasitic drain on the battery causing frequent non-start events. After determining that the draw from the data acquisition caused a significant portion of the parasitic drain on the SLI battery, the system was shut down temporarily to decrease the electrical draw on the batteries. This reduced the problem but did not eliminate it. The parasitic drain on the battery from the combination of factory electronics and the hydrogen system still drained the battery at a slow rate. This was noted to be a problem for H2ICE vehicles that went through periods of low usage, which were common among the drivers, principally as a result of off-site temporary duty assignments. Although data acquisition systems would usually not be present in production vehicles, the total parasitic drain is significant. A second generation of vehicles should give consideration to electrical loads that occur when the vehicle is off, and might benefit from the specification of larger and/or deep discharge cycle SLI batteries.

Due to the significant number of dead batteries events, the batteries were tested to check remaining capacity. Often this lead to a battery with severely reduced capacity requiring replacement. Each battery was replaced on average two times. This is significantly more often than batteries in standard commercial vehicles.

SUMMARY/CONCLUSIONS

The H2ICE vehicles demonstrated that they are an equivalent vehicle to the hybrid electric gasoline SUVs in meeting Government personnel and Government contractor personnel requirements for non-tactical vehicles at military installations. The fuel economy was shown to be similar to the standard hybrid electric gasoline SUVs, showing that the change in fuel did not significantly alter the vehicle efficiency. The main differentiation between the vehicles was the range that the vehicle could drive before refueling and hydrogen fuel availability. The vehicles were refueled using renewable hydrogen produced from solar electrolysis; as a result, these vehicles displaced approximately 1,113 gallons (4213.2 liters) of gasoline.

The major repairs and maintenance were generally minor part-swap replacements. The preventative maintenance for changing the oil had a greater requirement for the H2ICE vehicle than a standard SUV to verify that the oil did not have water contamination. The 12V SLI battery required additional attention if the vehicle was going to be in a state of disuse, but did not have an issue when the vehicle was utilized regularly. These were the maintenance actions that occurred at a frequency different from a standard gasoline vehicle.

Many of the performance issues noted by the drivers were related to systems not exclusive to the H2ICEs and were easily addressed through proper training on why the vehicle performs in that manner. Range anxiety was prevalent due to the low number of hydrogen refueling stations available, though that concern would be addressed with an expansion of the refueling infrastructure and not by modifications to the H2ICE vehicles.

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CONTACT INFORMATION

Steven Eick, Engineer. steven.eick1@us.army.mil Office telephone: 586-282-8029

Greg Whiting, Project Manager. Greg.whiting@sesincusa.com Telephone: 808-343-5445

ACKNOWLEDGMENTS

Thank you to all the H2ICE Drivers for your dedication to evaluating the technology and your honest and timely feedback on the vehicles.

DEFINITIONS/ABBREVIATIONS

DOD	Department of Defense
eCVT	Electrically controlled continuously variable transaxle
gge	Gallon of Gasoline Equivalent
H2ICE	Hybrid Hydrogen Internal Combustion Engine
JBPHH	Joint Base Pearl Harbor Hickam
NAC	National Automotive Center
PACOM	Pacific Command
SLI	Starting, Lighting, and Ignition
SUV	Sport Utility Vehicle
TARDEC	Tank Automotive Research Development, and Engineering Center